3 The MINERνA Project

3.2 Photomultiplier Tubes

3.2.1 Overview

Light from each of the $\sim$30,000 scintillators in MINERνA must be converted to an electrical pulse which carries accurate timing information and has an amplitude proportional to the energy deposited. This is done with photomultipliers (PMT's) of moderate gain and good linearity. To save cost, multianode PMT's with 64 pixels are used. The MINERνA detector will require 473 PMT's. Each PMT sits in a steel tube called a PMT box (Sect. 3.2.2). The inputs to this box are the clear signal fibers (WBS 2) bringing light from the scintillators and 2 light injection fibers (Sect. 3.2.4) which will track the gain during the experiment. Fast analog signals are fed to front end boards (FEB's) which sit on top of the PMT box. There, the signals are amplified, digitized, and converted to a fast timing signal (WBS 7).

We will use the R7600-00-M64 multi-anode photomultiplier tubes from Hamamatsu Photonics. These are 2 cm x 2 cm, 8 x 8 pixel PMTs, i.e. 64 pixels with effective dimensions 2 x 2 mm^2. Since this is the successor to the PMT's used by MINOS, we have good experience on which to build. For the overall system, we require standard properties of mechanical strength, isolation from light, electronic noise, and magnetic fields, and excellent calibration techniques. Standard concerns with PMT's include dark current and gain uniformity. With multianode PMT's, linearity and cross talk must be carefully considered. Finally, alignment of the fibers with respect to the pixels is also very important. Selection criteria will be imposed based on the dark count rate, and pixel gain uniformity. Alignment methods and performance criteria will be given in Sect. 3.2.3.

3.2.2 PMT optical boxes of the MINERνA detector

In MINERνA, optical cables must carry the light signals from the inner and outer regions of the tracking spectrometer and transport them to pixels of the the detector's readout array of photomultiplier tubes (PMTs) [1]. Each PMT is housed in an individual light-tight cylindrical enclosure ("box") made of steel. Each box provides the optical connection of fibers to PMT pixels in a way which ensures the crucial alignment. The boxes facilitate the routing of signal and voltage cables to-and-from the PMTs. Moreover they provide mechanical protection as well as significant shielding from ambient magnetic fields - the latter arising as result of proximity to the magnetized Near Detector of MINOS.

A new PMT box design has been developed for MINERνA, the essential features of which are described below. The design incorporates features of two optical box implementations which have been serving the MINOS experiment very well. As will be elaborated, MINERνA boxes accommodate one M64 phototube per box and so are more similar to "Alner boxes" of the MINOS Near Detector, rather than MINOS MUX boxes of the Far Detector (which serve three M16 PMTs per box). However, in contrast to Alner boxes, the MINERνA design utilizes construction-standard steel extrusions to achieve fabrication economy and improved magnetic shielding. Fabrication and quality assurance testing of a total set of 550 optical boxes is required to fulfill MINERνA's immediate deployment need (473 boxes) plus its operational maintenance needs upon extended operation. (The latter includes the experiment's need for hot spares and spare components, plus a small allowance for production wastage.) Manufacture of the optical box array and its delivery to the staging area at Fermilab will be carried out using two coordinated, independently operating assembly "factories" which are being set up at Tufts and Rutgers universities.

Functions of PMT boxes

PMT box functions addressed by the design developed for MINERνA are listed below. Design aspects which relate to these functions are elaborated in the Sections following.

1. *Boxes provide precise alignment of signal fibers to PMT pixels:* Alignment is made using machined mounting cookies which capture the input fibers and press them onto the face of each M64 PMT; the PMT is held via a machined holder, to which the cookie mates in a precise way and with unique orientation.

2. *Boxes provide light-tight enclosures for the PMTs:* Each box consists of a hollow cylindrical steel hull with endplates at either end; each endplate is augmented with a gasket and RTV seals which ensure that no light can leak in from the outside.

3. *Boxes provide mechanical protection for the delicate and valuable M64 PMTs:* Construction-standard Fe extrusions are used to provide rugged and inexpensive enclosures.

4. *Boxes provide magnetic shielding for the PMTs:* Ambient magnetic fields exceeding 5 gauss can degrade PMT efficiency; ambient fields in spaces to be occupied by the detector have been measured and are in the range of 2 to 16 gauss. In the deployed orientation, axes of MINERνA boxes will be nearly transverse to residual B-field from MINOS and will provide a factor ten field reduction from the box exterior to the inner, central location of the PMT.

5. *Boxes provide optical fiber and electronic voltage and signal routes to the PMT:* Routing of fibers and cables to/from the box interior is made via connectors and ports which breach the endplates.

6. *Boxes provide mounting surfaces for circuits of the Front-End Board (FEB):* Within a MINERνA PMT box, a part of the FEB plugs directly into an electronics endplate feed-through board, while the remaining circuitry is housed in an aluminum tray positioned axially along the outside the the cylindrical hull.

7. *MINERνA boxes provide the interface between the PMTs and the light injection (LI) calibration system:* Light from a reference LED is routed via optical fiber through the fiber feedthrough endplate of each box and terminates within the box in a diffuser piece. The PMT response to diffused light which is propagated through narrow area around the optical fibers as they threaded through the cookie, is used to monitor its performance.

MINERνA PMT box mechanical design In the Alner boxes build for MINOS, the box enclosures were made from thin-wall plate, creased and welded into a rectangular box. In MINERνA, an equivalent structure is obtainable more economically by utilizing construction-standard hollow steel extrusions of cylindrical cross-section. These can be capped by spot-welding of flanges onto each end, to which flat steel endplates can be screw-mounted.

A highly useful feature of the Alner boxes is that the metallic enclosure forms an outer shell from which the inner components can be separated. The latter are mounted on a rigid structural frame which is inserted along the axis of the rectangular enclosure. Using this arrangement, easy access to all pieces which must eventually reside within the box, is available during assembly and alignment, e.g. the loaded cookie and its fiber bundle and the PMT-holder-base assembly. This same fabrication stratagem has been adapted for MINERνA. In the latter implementation, four rigid mounting rods are attached to the interior side of the fiber feed-through endplate. The PMT-holder assembly has a receiving hole pattern which allows it to be slipped to the center of the rod frame. The unit thusly mounted can then be inserted axially into the cylindrical hull. These mechanical aspects are readily discerned in the photo of Fig. 1 which shows a partially assembled MINERνA box prior to insertion of the frame.

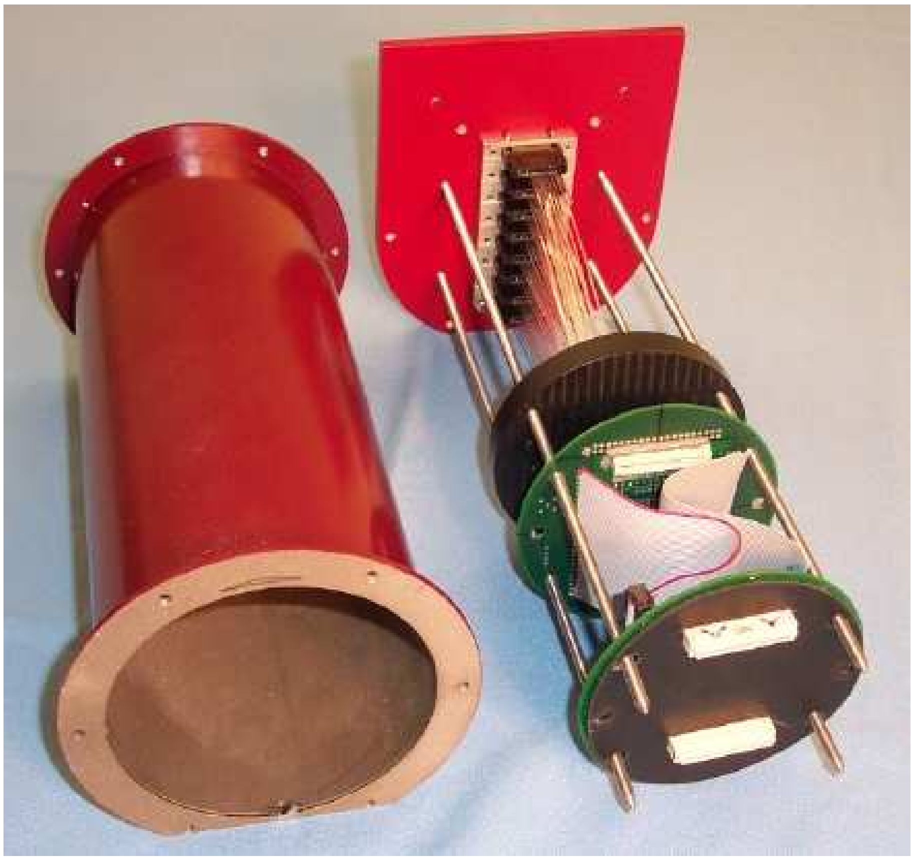

Figure 1: MINERνA PMT optical box prior to assembly. The rod frame which holds the fiber cookie plus holder plus PMT (right) is inserted axially into the surrounding steel enclosure (left).

By using construction-standard steel extrusions, it is possible to have a relatively thick-walled box at modest cost; for MINERνA boxes, wall thickness of 2.36 mm has been chosen. The result is a box which provides a useful degree of magnetic shielding for the inner region occupied by the PMT.

Alignment of fibers to pixels

Within each box, the enclosed PMT will be in optical contact with the polished ends of the bundled fibers which it reads out. This contact is made possible via termination of the fiber bundle with a precisely machined fiber mounting “cookie” - shown in Fig. 2 - which holds the polished fiber ends. Registration of the fiber-loaded cookie to the PMT is mechanically precise. This is made possible by a precision mounting “holder” which captures the PMT and which receives the cookie; the correct positioning of fiber ends onto the PMT pixel pattern is assured via alignment pins on the holder. A holder piece is shown in Fig. 3. The fiber mounting cookie and the PMT holder are precision pieces CNC-milled from Noryl plastic. The cookie, precision holder, and their relation to the PMT, are indicated in

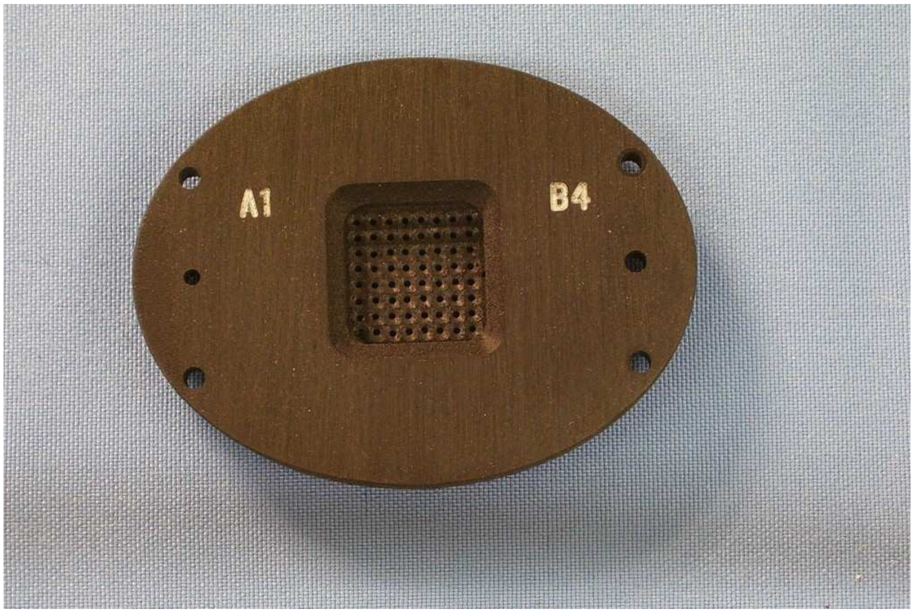

Figure 2: Optical fiber "cookie". The hole pattern accommodates the sixty-four fibers which are routed to the box by eight fiber cables.

the photograph of Fig. 4.

It is highly desirable to ensure that at the PMT pixel grid, signals originating at neighboring locations within the detector receive a degree of isolation; otherwise, pixel to pixel cross-talk can obscure the assignment of pulse heights to track hits. In order to provide a degree of isolation, a simple weave pattern is used in the routing of fibers onto the cookies. The weave pattern is a "row-pair interleave weave"; the fiber-to-pixel association which it introduces is shown in Fig. 5.

Box endplates

As indicated previously, each end of the box hull is closed off with a steel endplate. Connections to the box interior are made via various connectors and ports which breach the endplates. The box interior layout with endplate connections can be seen in the cutaway view of Fig. 6.

All of the electrical connections are brought through one endplate (the "electronics endplate"), whereas the optical fiber connections and also the connection to the LI diffuser are brought through the opposite endplate (the "fiber feedthrough endplate"). Consequently the endplates are quite different, and the implementation of light-sealing is different. At the electronics endplate, the light seal is made via a thin-rubber gasket. The fiber feedthrough endplate however, is mechanically more complicated due to the port arrangement needed for eight separate fiber cables. On the interior surface of this endplate, sets of small aluminum clips with pins are used to secure the eight plastic box connectors. Light sealing of the plate is accomplished using a sealing compound which is poured into a cavity on the outside of the endplate. The feed-through box connectors can be seen in the foreground of the photograph of Fig. 7. The sealing cavity, prior to epoxy-loading, is also clearly visible.

Box magnetic shielding of the PMT Measurement of the magnetic fields in Near Hall regions immediately upstream of MINOS was carried out by M. Bonkowski [2]. An ambient magnetic field of five

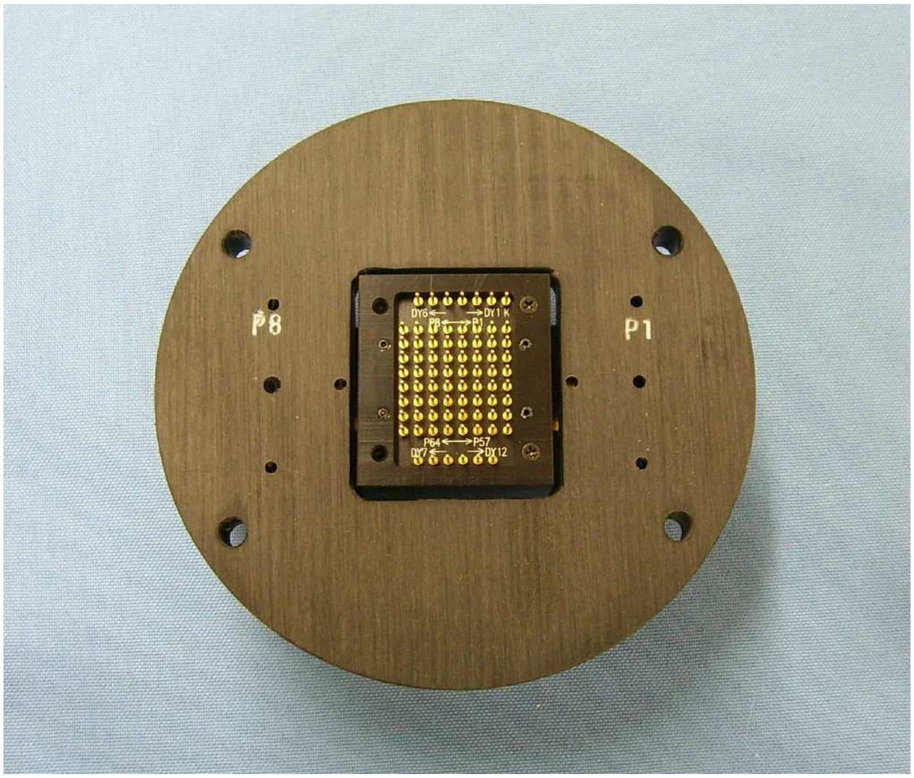

Figure 3: The precision PMT holder. The PMT is held so that its pixel grid relates to the holder locating pins in a precise and reproducible way.

Figure 4: Photograph shows a fiber-loaded cookie, oriented towards the face of the precision holder onto which it is to be mounted using alignment pins. The PMT plus its holder - shown on the right - is affixed into the holder (at the PMT testing sites) in a way which relates the PMT pixel grid to the locating pins of the holder.

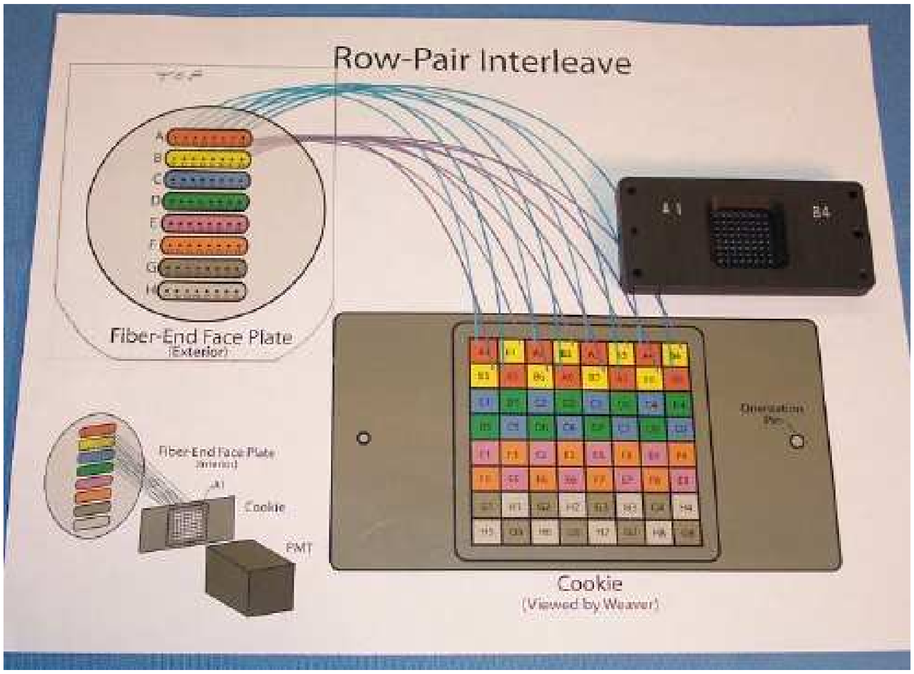

Figure 5: The weave used in placing optical fibers into the cookie grid. The resulting row-pair interleave pattern is designed to minimize signal reconstruction confusion arising from pixel-to-pixel cross-talk.

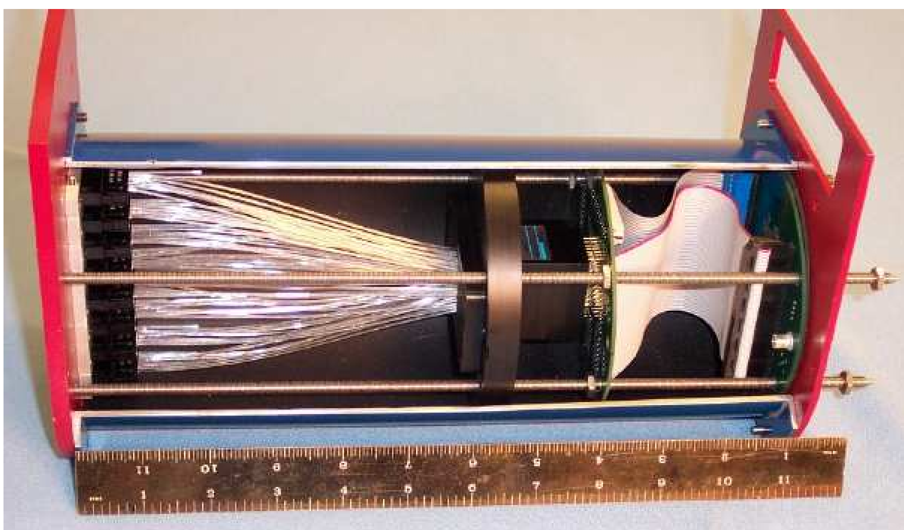

Figure 6: Interior structure of an optical box: Optical fibers enter from the outside via connectors through the fiber feedthrough endplate (left side) and terminate on the cookie. The pixel grid of the M64 phototube is registered to the cookie hole pattern via precision mounting pins which are part of the PMT holder. Cables provide voltage and signal connections to the PMT from connectors which breach the electronics endplate (right side).

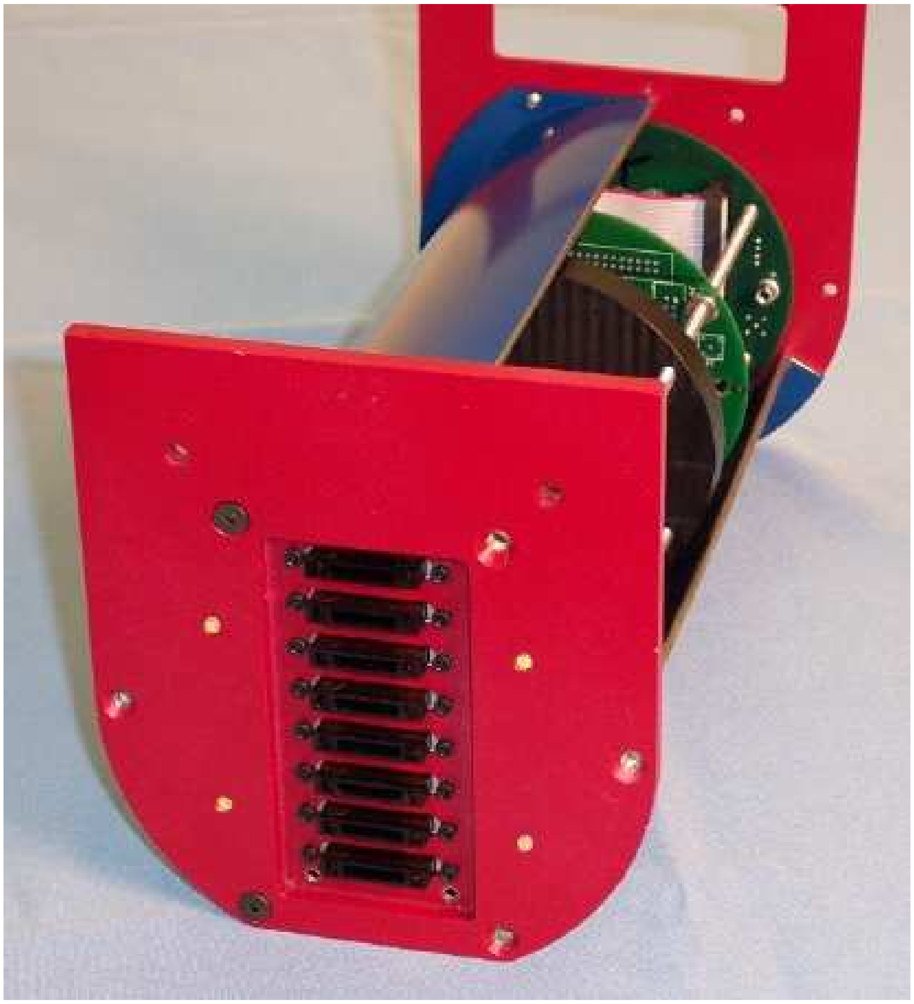

Figure 7: Fiber feed-through endplate - exterior view.

gauss exists throughout the area to be occupied by the MINERνA detector. In the space immediately downstream of MINERνA and in front of the first magnetized plane of MINOS, the ambient field will be larger; the measurements show ten gauss at the downstream end of MINERνA, increasing to 21 gauss within a few inches of the MINOS front plane. Ambient field of the latter magnitude, if it were to be allowed to pervade the volume occupied by MINERνA's M64 PMTs within their optical boxes, could be deleterious to phototube performance. Measurements of M64 response to magnetic field are provided by Hamamatsu; it is observed that PMT output is reduced to 92% in the presence of an axial magnetic field of five gauss (Hamamatsu curves are reproduced in Ref. [3]. Consequently it is required that MINERνA PMT boxes provide, in addition to a light-tight enclosure, an environment for the PMT which is well shielded magnetically.

This goal is achieved in the MINERνA design as the result of two features: Firstly, the wall of the box cylindrical hull is made of 2.36 mm steel; this is distinctly thicker than either of the MINOS box implementations which have adequately provided magnetic shielding for PMTs deployed in environments similar to MINERνA's Near Hall location. Secondly, cylindrical containers are especially effective in shielding from ambient fields provided that the cylinder axis is tranversely oriented relative to the ambient field direction. The latter situation is in fact the case for deployment configuration planned, wherein the cylindrical box axes are oriented transversely and radially with respect to the spectrometer's central axis. In this orientation, PMT box axes are everywhere roughly transverse to the ambient toroidal field arising from the MINOS coil current. An additional design feature, which has been thoroughly explored using Hall probe measurements (see below), is the capability of each box to readily accommodate a mu-metal foil insert should it prove necessary. The foil insert is to be wrapped cylindrically, so that it defines an interior volume within which each PMT resides. The foil acts like a conducting path for B-field lines, drawing them away from the PMT and routing them around it.

Magnetic shielding capabilities of the MINERνA PMT box were examined by placing an assembled box in various orientations within 20 gauss ambient B-fields created using Helmholtz coils. A Gaussmeter with axial and transverse Hall probes was used to measure the leakage field pervading the box interior. It is observed that the MINERνA box provides a field reduction factor (outside/inside-center) of about ten when the box axis is oriented transversely to the external B-field; in the most unfavorable orientation - box axis parallel to ambient $\vec{B}$ - the reduction factor drops to four. With the introduction of a mu-foil inner surface, the reduction factor with unfavorable box orientation is increased from factor four to factor ten. Fortunately, the magnetic shield provided to MINERνA PMTs appears to be sufficient in either orientation and without the mu-foil augmentation, provided that the MINERνA detector is operated without its own magnetic field. Details of magnetic shielding measurements with the MINERνA box design can be found in Ref. [3].

Mounting the box array on the detector Each MINERνA box has two steel mounting pins which are welded to the fiber-feedthrough endcap. The pins allow each box to be loaded - with fiber connectors radially inward, electronics endcap radially outward - into a structural framework mounted atop the spectrometer's two upper/outer surfaces. The framework provides a standoff space from detector surfaces to facilitate fiber cable routing and their connections to the PMT box array. The mounting arrangement positions the circuits and connections of the signal Front-End boards on the elevated, outer surfaces of the boxes, thereby facilitating access to them for diagnostic work and for repair. The layout is designed to allow rapid removal and replacement of individual PMT boxes, should that be needed during running of the experiment.

Factory production Mass production and checkout of PMT boxes requires that dedicated factory fabrication areas be set up. Moreover, frequent utilization of modern, staffed machine shops is a prerequisite for timely box array manufacture. In MINERνA these resources - in the form of dedicated university shops - are available at two factory sites which are being developed at Tufts and Rutgers universities. The factory sites will operate concurrently and independently. In steady-state operation, each factory will produce functional boxes at a rate of approximately one box per working day. Workstations are being deployed at the factories which will carry out the following:

1. Machining of precision PMT holders and fiber mounting cookies (Tufts).
2. Machining of box endplates and flanges.
3. Spot-welding of endplate flanges to cylindrical hulls.
4. Electrostatic painting of box cylinders and endplates.

5. Optical fiber weaving into cookies and epoxying.
6. Cutting and polishing of fiber-loaded cookies.
7. Quality assurance (QA) testing of assembled PMT boxes.

Figure 8: A loom rig is used to thread optical fibers into cookies according to the weave pattern of Fig. 5. The central assembly is mounted so as to maximize hand access. Vertical struts on either side accomodate stabilizing supports (preferred by some operators).

Instrumentation has been designed for each workstation to facilitate execution of the task at hand. For example, the weaving and epoxying of optical fibers into cookies (task 5 above) is greatly facilitated by use of a “loom rig”; the current prototype is shown in Fig. 8. The rig holds a set-of-eight ODU cables and their fibers optimally for ease in implementing a weave.

Tasks which involve weaving of cookies, mounting of components into the endplates and onto the internal frame, final assembly of boxes and their QA testing, will be carried out in clean room assembly areas. Factory daily operations, from arrival of parts to shipment of completed boxes, will be monitored and progress will be recorded in a web-accessible database.

Assembled optical boxes will be shipped by commercial trucking to Fermilab. For this purpose, shipping containers will be built which accommodate forklift handling and which will hold a convenient (large) number of boxes.

3.2.3 PMT Alignment and Testing

The Hamamatsu multianode PMT (R7600U-00-M64) was selected for use in MINERνA. This type of multianode PMT is an incremental design improvement from the R5900-00-M64 phototubes used in several high energy experiments, including the MINOS near detector. The R7600U-00-M64 PMT meets the design requirements of the experiment (to be elaborated below); the high density maximizes the channel/$ ratio.

Alignment The first task of the James Madison University (JMU) group is to align each PMT channel with its corresponding optic fiber. The actual part number delivered by Hamamatsu is H8804-MOD2, which consists of the actual PMT epoxied in a rigid jacket or housing. This packaging, while saving a couple of manufacturing steps (manufacturing the jacket and gluing the PMT in it), does not eliminate the need of aligning the PMT pixels with respect to the optical fibers. The MINERνA PMT optical boxes (see Sect. 3.2.2) contain precision–machined mounting cookies which capture the 8×8 array of optic fibers and press them on the face of the PMT. The optical fiber cookies are precision-mounted to the PMT holder using alignment pins. To ensure the unambiguous orientation of the cookie with respect to the PMT holder, different diameter pins are used. The only degrees of freedom allowed are between the PMT holder and the jacketed PMT.

Each PMT has 4 alignment "dots" provided by the manufacturer. Regular cookies are opaque making difficult to use for alignment purposes. A special, transparent cookie outfitted with cross-hairs will be used instead. A schematic of the alignment stand built at JMU is shown in Fig. 9. The PMT is held by the (green) holder shown in the middle of the picture, mounted on top of a set of X–Y–ϕ stages. The alignment cookie is fixed to the top plate of the device (shown in gray). The PMT can be moved using the stages with respect to the cookie–PMT holder assembly. A high resolution digital camera (Nikon...) is used to visually check the alignment. Based on the resolution of the camera we estimate that we can obtain a 10 μm alignment precision. The PMT holder has holes drilled and tapped for 4-40 screws that are used to "lock–in" the alignment once the PMT is properly positioned. These screws pass through slightly oversized holes drilled through the "ears" of the PMT jacket. A picture of the alignment station at JMU is shown in Fig. 10.

PMT Testing Once aligned, each phototube will be subjected to a series of tests to determine its suitability for use in the experiment. These tests are designed to complement and augment the testing done "in–house" by Hamamatsu and are driven by the physics requirements of the experiment.

The general properties of the R7600U PMT are listed in Table 1. The characteristics of the R7600U PMT are listed in Table 2.

To further understand the real meaning of some of the figures listed in Tables 1 and 2 we asked the Hamamatsu representatives to elaborate on the tests they conduct prior to delivery of PMTs. Hamamatsu tests all PMTs shipped and provides a data-sheet for each PMT that includes S_k (cathode sensitivity in μA/lm), S_p (anode sensitivity in μA/lm), dark current, Blue Sensitivity Index, and Gain (calculated from S_k, S_p). Dark current information is provided on our final test data sheet shipped with the PMTs and at no additional cost/delivery time. But, the dark current value is a total value and is not specific for each anode. Gain is calculated using the S_k and S_p values provided on the final test data sheet. Gain = S_k/S_p and this value is provided as well. Hamamatsu will provide a relative gain versus channel map and will guarantee no deviation outside the MINERνA spec of 3:1.

Parameter	Description/Value	Unit
Spectral Response	300–650	nm
Peak Wavelength	420	nm
Photocathode Material	Bialkali	
Photocathode Min. Effective Area	18×18	mm
Window Material	Borosilicate Glass	
Dynode Structure	metal channel dynodes	
Number of Stages	12	
Weight	30	g
Suitable Socket	E678-32B (sold separately)	
Operating Ambient Temperature	-30–50	^{o}C
Storage Temperature	-30–50	^{o}C
Supply Voltage	900	V
Average Anode Current	0.1	mA

Table 1: General properties of the R7600U phototube

Parameter	Min	Typical	Max	Unit
Luminous (2856 K) Cathode Sensitivity	60	70	–	μ A/lm
Quantum Efficiency at 420 nm	–	20	–	%
Blue Sensitivity Index	7	8	–	–
Luminous Anode Sensitivity	4	140	–	A/lm
Gain	5×10^5	2×10^6	–	
Anode Dark Current	–	2	20	nA
Anode Pulse Rise Time	–	1.4	–	ns
Electron Transit Time	–	8.8	–	ns
Transit Time Spread (FWHM)	–	0.26	–	ns
Pulse Linearity ($\pm 2\%$)	–	30	–	mA

Table 2: R7600U phototube characteristics at 25^{o}C.

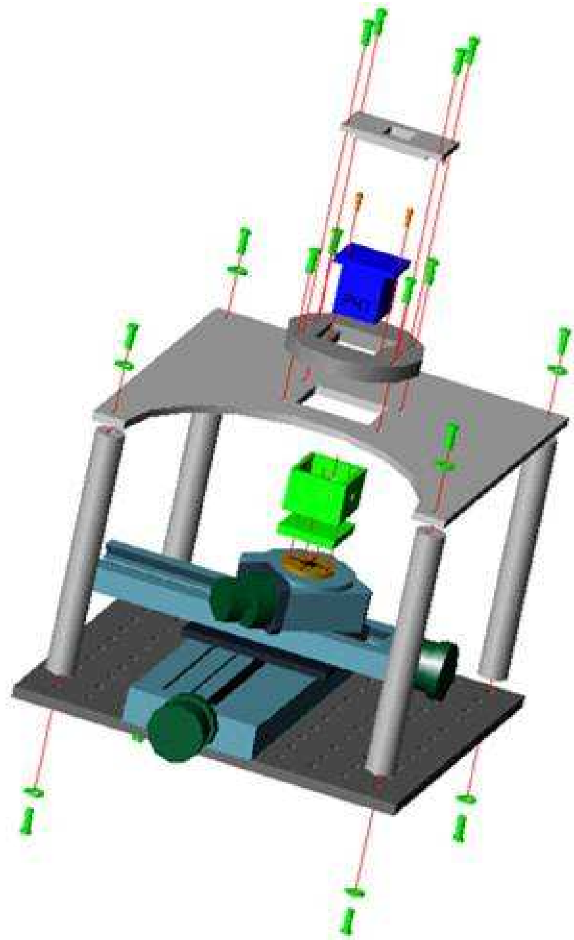

Figure 9: Schematic of the Alignment Stand

As seen from the above, Hamamatsu Photonics is mostly concerned with obtaining numbers that globally characterize their product. While this type of information is suitable for rejecting defective PMTs, it does not provide the channel–by–channel data needed for MINERνA use. As outlined in the next section, the MINERνA collaboration will build a test stand enabling us to perform these more detailed tests.

The Test Stand The MINERνA test stand will be designed to test 5 PMTs at a time. Automation will allow a complete series of tests which will last less than 24 hours for a batch of 5 PMTs. The test stand will use 448 (= 7 x 64) channels of MINERνA electronics, and will assume a DAQ rate of 500 Hz and integration time of 12 microseconds. The conceptual design of the test stand is shown in Figs. 11 and 12.

The test stand will consist of:

- a) Frame: A relatively light frame which will consist of two separate sections that fit precisely together. Fig. 13 shows two views of the frame. The upper part will hold the light injection

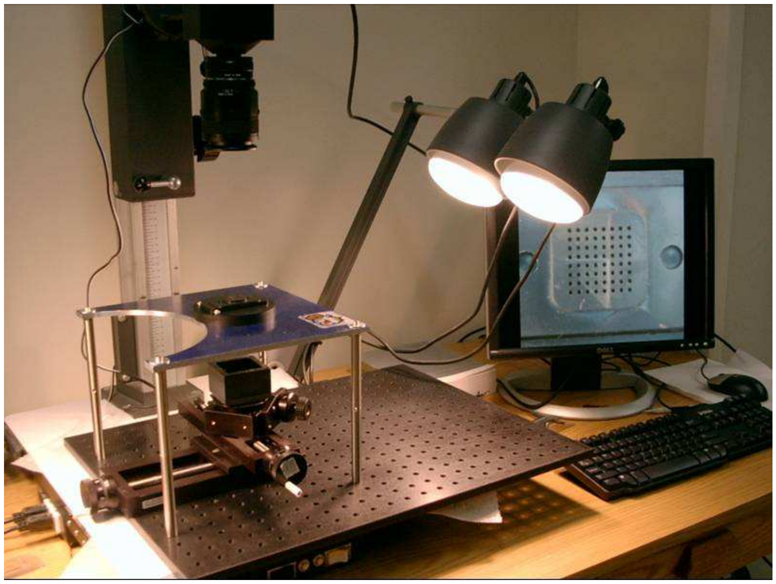

Figure 10: JMU Alignment Stand

manifold. The lower one will have a plate on which several parts will reside: the traveling stages, the LED, the filter wheel, and the monitoring PMT. The relative alignment of the two frames is important to ensure that the light pen travels in x–y–z directions matching the positions of the fiber bundles. This arrangement of the support structure in two sections allows for easy transportation of the assembled test stand.

- b) Fiber optic light injection manifold: this is placed in the upper section of the frame. It will provide light from an LED to 6 M64s, one of which will be permanent and will serve as a reference PMT. The concept is shown in Fig. 12. The upper plate will hold 6 cookies+PMT's and the lower plate will route fibers illuminated by the LED to the PMT's. Each cookie will accept a bundle of 64 clear fibers, each 1.2 mm in diameter (same as will be use for scintillator signals in the experiment). The lower plate has 64 holes, each of which can be illuminated by the LED. Each hole holds 6 fibers which are routed to the same pixel in each PMT in the upper plate. Thus, 64 bundles of 6 clear fibers each will emerge from the lower plate and they will get reorganized into 6 bundles of 64 fibers to match the PMT. Each LED position will send light to 6 pixels and when the LED has been in all 64 positions all 6×64 pixels will have been illuminated.

- c) A system of x–y–z stages carrying an LED light pen which injects light sequentially to all 64 fiber bundles. The LED travels with the system, so that no changes to the optical readout system (e.g. fiber bending) occur during the movement from bundle to bundle. The stage motion will be controlled by the DAQ PC. The LED light will go through several feet of WLS fiber to emulate the frequency distribution from the real detector. A light diffuser in each hole in the lower plate will send light uniformly to all 6 clear fibers. Before the light reaches the light pen it goes through a set of 7 neutral density filters mounted on a filter wheel controlled by a moving ϕ stage. This enables the study of the PMT response versus light intensity. A light monitoring PMT will sample the light intensity prior to injection.

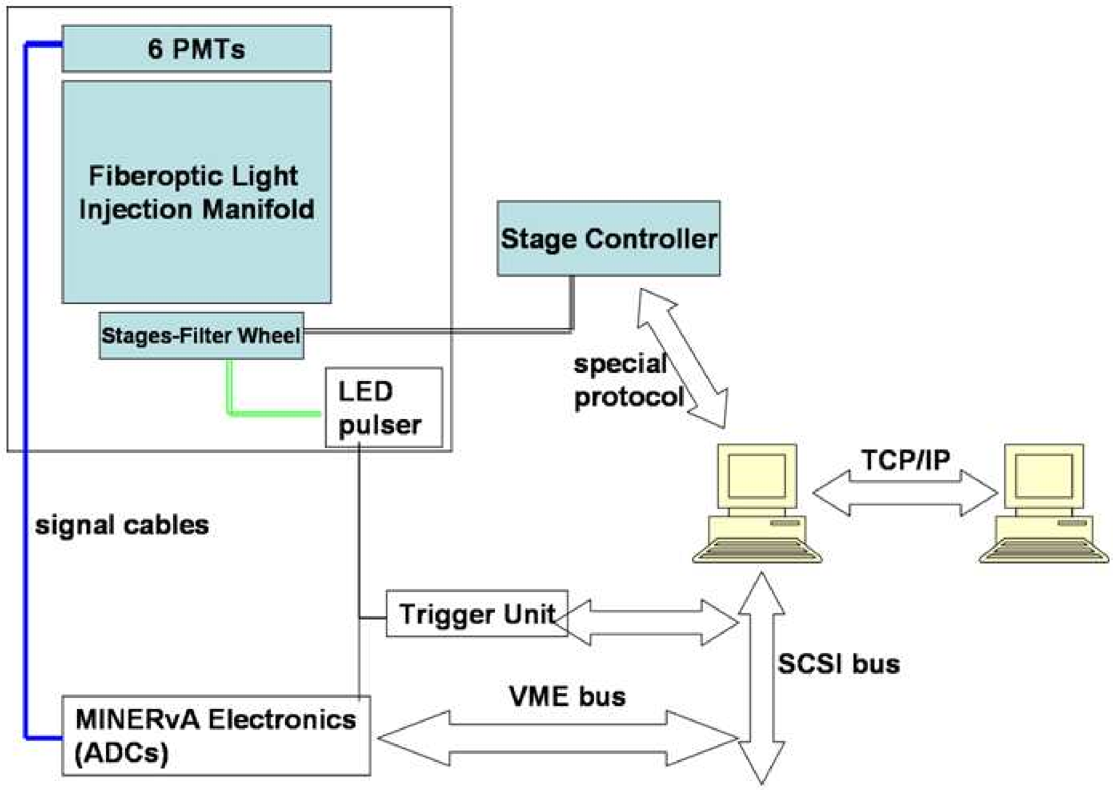

Figure 11: Schematic of the Test Stand

- d) MINERνA Electronics: The signals from the M64s are amplified and digitized in the same front end boards (FEB's) as will be used in the experiment. The data is then read out through VME. to the DAQ computer.

- e) Trigger: A computer controlled trigger unit will trigger the LED pulser and will provide an integration gate for the ADCs.

- f) Data analysis PC: this computer will receive the data from the DAQ computer via TCP/IP connection. Analysis done here will provide monitoring data, histograms, tables, and summaries; it will build the information that will be stored the data base.

Athens and Fermilab are responsible for the design of the test stand. The frame is constructed at Fermilab. The mounting plates and cookies are done by Tufts, whereas the fiberoptic 64 to 6 distribution will be done by Rutgers. The overall assembly of the system, including MINERνA electronics, DAQ, software, and commissioning will be done by Athens. After successful initial operation the test stand will be installed at JMU for the testing of the MINERνA PMTs. The PMT alignment will be done at JMU before the PMT's are mounted to the test stand.

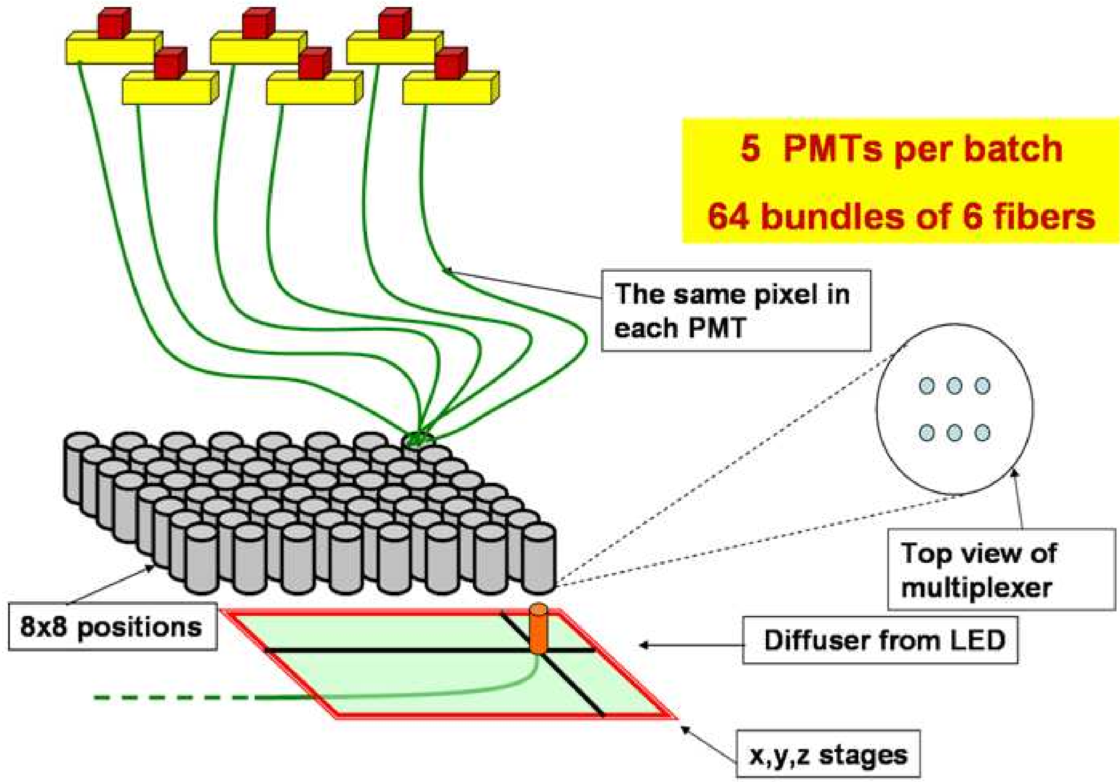

Figure 12: Schematic of the fiber optic injection manifold.

Initial Tests Each PMT will be subject to a series of short/quick tests. These tests will determine the optimum operating point via a high voltage scan. The optimum operating setting will have a gain of about 3×10^5 and a good one photoelectron resolution. Also at this stage we will look for dead pixels as well as grossly misaligned PMT assemblies.

Dark current The main concern is that high dark noise leads to unacceptable dead time and/or large event size. A dark noise pulse (defined as the signal produced by the PMT when no light input is present) produces a $\sim$300 ns dead time, evenly split between the integration time and the reset time. This represents a 3% dead time for the whole PMT (assume $10\mu s$ beam pulse). For a 1 kHz dark noise rate the probability of having a dark noise pulse during the $10\mu s$ beam pulse is 1%. Overall this amounts to a 0.03% dead time, assuming all tubes have the same dead time rate. Past experience (MINOS) with M64 phototubes shows that only 5% of tubes exceeded the 1 kHz rate. For MINERνA we propose to test/reject tubes that have a dark noise rate of 5 kHz in any pixel. The summed rate for the full PMT will have a higher limit.

Figure 13: The test stand frame.

Testing procedure The high voltage on the PMTs will be set to the nominal operating point and the system will be kept in the dark for 1 h. During this time (and the rest of the test) the temperature will be monitored/kept constant to within 2 ^oC. The DAQ will be pulsed and $\sim$10 M events will be accumulated. Counting how many times the integrated charge was greater than the 1/3 p.e. threshold will provide a measure of the dark current.

Linearity Non-linearity in the PMT response (energy vs. npe curve) leads to inaccurate energy measurement, possibly affecting particle identification. Observable non-linearities of the signal may result from space charge effects due to the small size of the M64 dynodes. One should expect to see non-linearities in the PMT response for large input signals. The MINOS experiment found non-linear effects starting at 70–300 pe, phototube dependent. Hamamatsu Photonics quotes a 5% deviation at 0.6 mA, which corresponds to $\sim$87 pe assuming typical MINERνA conditions ($\sim$7 ns pulse width and 3×10^5 gain). The typical MINERνA signal will produce $\sim$5 photoelectrons/MeV. Electromagnetic showers deposit about 20 MeV per detector element (extruded triangular prism), for a total of $\sim$ 100 photoelectrons. The largest non-linear effects documented by MINOS were of the order of 10% at 300 pe. Even assuming a worse case scenario of 10% non-linear effects at the expected 100 pe, a modest measurement (20% accuracy) will help keep this uncertainty at a 1-2% level.

Testing procedure A remotely controlled filter wheel will vary the light intensity received from the LED. The data set will comprise of 10,000 pulses/pixel for each light intensity level. By first measuring the tube's response to a preselected reference level, say 12 p.e., the expected response, based on an assumption of linearity, may be calculated as a product of the incident light intensity, the gain, and the pixel efficiency. The incident light level is determined from the relative opacities of the filters between the reference and current points. The ratio of the measured/expected charge, when plotted over the expected dynamic range for MINERνA, will indicate the PMT's linearity.

For this test to be useful, the test stand setup must be a good match to the actual experiment. We will use the same cookie, PMT, and electronics as the experiment. The blue LED will be triggered with a fast pulser to match the experiment and a few meters of WLS fiber will shift the frequency spectrum to approximate what we will see in the experiment.

Phototubes are expected to be linear within 1% up to 80 pe. The accepted PMTs will be further tested up to 400 pe and the best tubes will be selected for the central region of the detector.

Inter–pixel cross talk For the purpose of this document cross talk is defined as the process in which one pixel of a PMT provides a measurable output when other/adjacent pixel(s) is/are illuminated. This mechanism gives incorrect energy measurements and deteriorates the position resolution (if between adjacent detector elements). Both of these affect pattern recognition/particle identification and further complicate tracking. The origin of cross talk are either electrical (charge leakage during amplification from one channel to another) or optical (light from one fiber ends up on a different pixel).

The MINOS experiment found the electrical cross talk to be small, consistent with the 2% value quoted by Hamamatsu Photonics. The amount of electrical cross talk to nearest neighbors is less than 0.5%.

Optical cross talk is potentially more damaging, as it affects the position resolution and thus tracking. Misalignments between the PMT and its holder would result in large cross talk effects, although gross misalignments should be easy to spot. This type of effect is more important for minimum ionizing particles, where the overall number of photoelectrons is small (10 pe for MINERνA). For these kind of yields an extra pe causes an error of about 10% in position resolution (about 2 mm). Optical cross talk is minimized in MINERνA using the weave-pattern described in Sect. 3.2.2 (adjacent triangles are mapped to diagonals on the PMT face).

Testing procedure Each individual pixel will be pulsed with an amplitude of about 30 pe for 10,000 pulses. The cross talk observed should be less than 5% of the primary signal for diagonally opposite pixels and less than 10% for adjacent pixels. The procedure will be repeated (with less counts/setting) for two more intensity levels.

Pixel–to–Pixel Uniformity The average gain for MINERνA will be around 3×10^5. Individual pixels will exhibit larger or smaller gains. These variations need to be contained so as to not exceed the dynamic range of the MINERνA electronics. It is anticipated that the MINERνA electronics could accommodate a 3:1 range. Previous testing done by MINOS found very few tubes exceeding this limit. The 3:1 pixel–to–pixel gain variation limit is explicitly requested in the contract with Hamamatsu Photonics and will be tested for each tube.

Efficiency Low efficiency tubes will adversely affect the photon statistics. This is especially important for minimum ionizing particles where the experiment cannot afford significant decreases in efficiency. Hamamatsu Photonics gives a typical value of 70 μA/lm, with a minimum efficiency of 60 μA/lm. Our preference would be to request that all tubes have at least 70 μA/lm luminous cathode sensitivity.

The MINERνA PMT test stand does not provide a method for measuring the absolute quantum efficiency (QE) of the PMTs. However, the procedure outlined below can measure an "effective efficiency", i.e. the product of the QE and charge collection efficiency, integrated over the whole light spectrum of the diode/fiber combination.

Testing procedure The monitor PMT will be used to correct for variations in the light input to 1 % or better. This correction will make possible comparisons between the numbers of photoelectrons detected on a pixel/phototube basis. These effective efficiencies can be subsequently normalized to one/few PMTs for which the manufacturer provides an absolute efficiency curve(s).

Summary The tests listed above will take an estimated 24 hours for 5 PMTs, including setup (loading and unloading PMTs) and data analysis.

3.2.4 Light Injection Calibration System

Any particle physics experiment with a large scintillator system such as MINERνA needs a rapid, simple, cost effective monitoring system. MINERνA has over 30,000 cintillators that must be installed, monitored, and at times replaced. The scintillators are read out with wavelength shifting (WLS) fibers which are joined to clear fibers that direct the light to Hamamatsu M64 phototubes. The PMT's sit in an iron PMT box. Confronted with the same problem, MINOS chose to inject LED light into the WLS fibers at the detector [4]. When injecting light directly into scintillators, nitrogen lasers are also used, e.g. at CDF. Our plan is to inject LED light into the PMT box, a simple and robust light injection (LI) calibrations system. The LI system is presently in the prototyping stage. Although we have a preliminary design, features are still being defined.

Function of Light Injection System

- The main application will be during installation and maintenance periods. A rapid check for dead channels and an accurate measurement of the gain of each PMT will be an important requirement.
- We also anticipate regular tests while taking data to supplement the calibration data coming from muons traversing the detector. In the MINOS near detector hall (where MINERνA will be located), the temperature is held constant to within a 6.5° range and the diurnal variation of about 1° is seen [5]. Thus, monitoring doesn't need to be continuous, but will be important whenever detector conditions change significantly (e.g. during dectctor maintenance, certainly when replacing phototubes.)
- A system such as this could also be used to measure the absolute gains non-linearities of each pixel in situ. This property will be measured as part of the PMT testing at JMU and Athens. The cost and complexity of doing a similar test with this system were deemed too large.
- As this is a moderate resolution experiment, the physics requirements are not thought to drive the design at present.

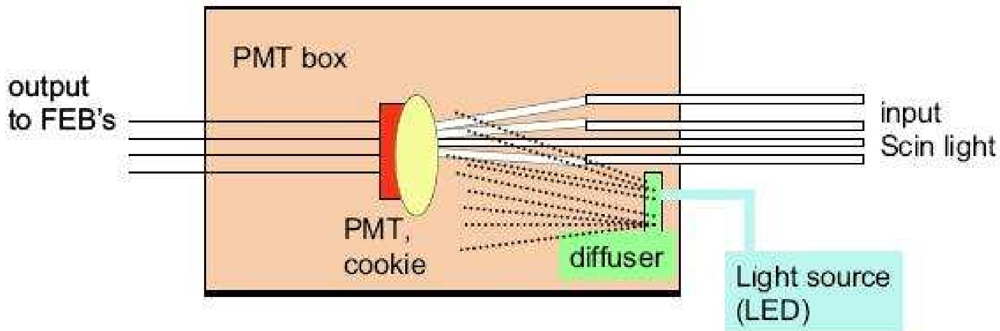

Figure 14: Conceptual picture of the way light will be injected into the PMT box. A simple prototype of this technique is discussed.

LI System Design Our design is a simplified version of the MINOS system. To keep costs down, we choose to inject LED light directly into the PMT box, some of which will be captured by the multianode PMT. Each PMT is serviced by 2 fibers to ensure that each pixel is uniformly illuminated. The light is spread out in the PMT box with a diffuser (see Fig. 14). This will enable a rapid and accurate gain check for the entire PMT.

The LED's sit in a Pulser Box near the detector; it is the most expensive part of the system. This box is presently being designed. It contains optical fanouts, the LED's and associated electronics. PIN diodes will be used initially to monitor the LED light output. They will be close to the Pulser Box. The output of this box will be 2*500=1000 fibers funneling light to the PMT boxes and the PIN diodes. The light from each LED will be fanned out to 50 PMT boxes in a cone/collar assembly similar to what MINOS used [4]. Thus, 20 LED's are expected to be enough to cover the full set of 473 PMT's and the PIN diodes with a sufficient number of spares. It is clear that the mechanical stability of these components is essential.

A diagram of the system is shown in Fig. 15. The entire system will be controlled as part of the MINERνA experiment data acquisition program. Groups of PMT's will be pulsed together (like MINOS) and all PMT's and the PIN diodes will be read out each time the calibration system is triggered.

The electronics required to control the LED's are not complicated. MINOS made 3 cards for power, LED driver, and control functions. A microprocessor on the control card will determine how the LED is fired - e.g. pulse height and width. We will start with the MINOS electronics and adapt to our needs. A very fast pulser (width stable at $\sim$ 10 ns) will be required to simulate the scintillator output signals. The overall cost is low when compared with the MINOS system.

The MINOS light injection system achieves $\sim 2\%$ accuracy with careful attention to construction details and a PIN diode to monitor the LED output. Although we don't need as much accuracy, we can easily obtain few percent accuracy with the system envisaged. The main usage for this system will be to monitor the overall gain of each PMT. At present, we plan to inject green LED light into the ends of a clear fiber. This will provide a moderately good match to the frequency spectrum of light from the scintillators.

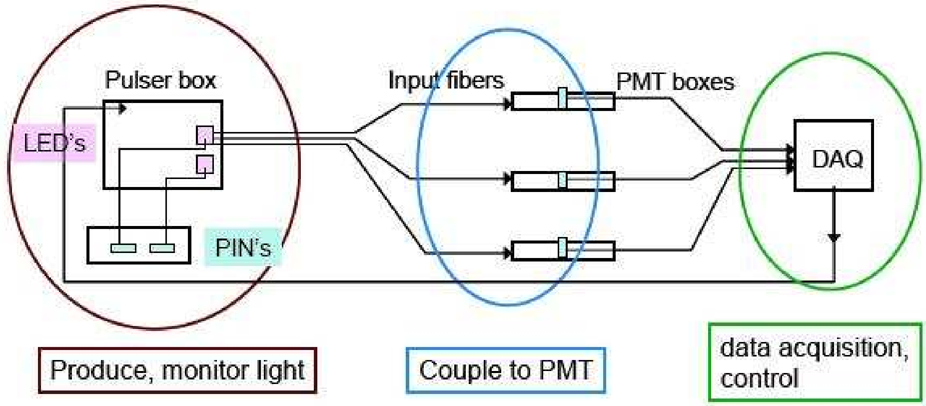

Figure 15: Design of the LI system. The DAQ computer will control the pulser box which will send out short pulses to each PMT. The repsonse will then be read out.

Construction Prototyping efforts to date have measured the ability to inject LED light into clear and WLS fibers. Green LED's couple well to either kind of fiber when the light is directed into the end of the fiber. For this test, the light transmitted through the fibers was measured with a PIN diode. We have also used the LED to trigger an M64 PMT in 2 realistic situations in a dark box(see Figs. 16 and 17). In the first test, light from the green LED triggered with a 4Vx100ns pulse produces a few pe signal in each PMT pixel using a prototype cookie. We have verified that at least 95% of the light reaching the PMT comes through the cracks between fiber and cookie. This test showed the need for small changes in cookie and PMT mount design to better protect the PMT from light other than what comes through the cookie. The second test (see Fig. 17) takes light from the same green LED as used in the first test. Using a cone/collar assembly from MINOS[7] (seen at the left side of the photo),light was fed through a clear fiber and aimed at the PMT in the approximate position the fiber will be located on the input plate to the PMT box. The light has to find its way through a 'forest' of 64 fibers simulating the real situation. The response for pixels on the far side of the forest was about a factor of 3 less than for pixels on the near side. When we added a diffuser (as seen on the right side of the photo), the response of all pixels showed less than 20% variation. This proves the concept in Fig. 14. Modifications to the PMT box are now complete.

Preliminary versions of the cone assembly are now being tested with the goal of defining properties of the LED and the density of clear fibers in the collar. We have purchased a fast pulser and will investigate LED's for speed, intensity, and stability. The light reaching the PMT's should not vary by more than a factor of 2 across the full set. We plan to complete prototyping efforts by end of 2006.

References

[1] The MINERνA Collaboration, *Proposal to perform a high-statistics neutrino scattering experiment using a fine-grained detector in the NuMI beam*, Fermilab Proposal P-938, e-print hep-ex/0405002; see Sect. 16.5.2.

[2] M. Bonkowski, *Magnetic Field Measurement Results*, MINERνA note MINERvA-doc-88-v1, (measurements of December 2004).

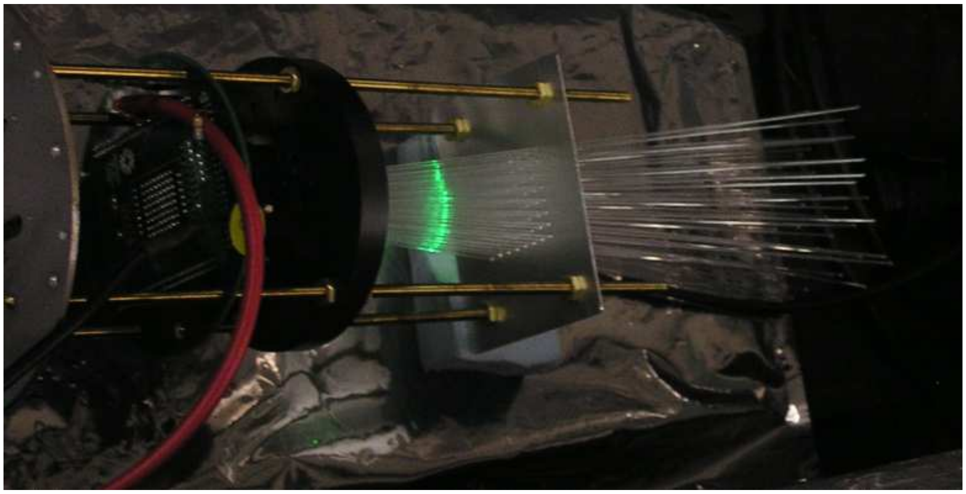

Figure 16: Prototype test of the light injection transmission to the PMT. The MINERνA PMT and prototype base (left) and cookie (hidden) are used. All 64 pixels have a fiber attached; the final design has a complicated weave, not used here. The green LED is in the approximate position of the light source for the final system. The frame, but not the iron shell, of the PMT box is used.

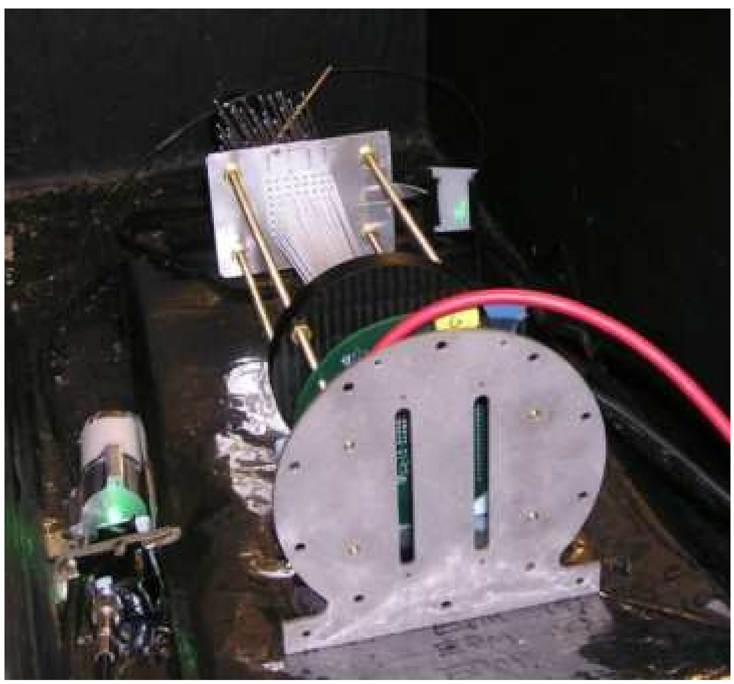

Figure 17: Prototype test of the light injection transmission to the PMT, an extension of the test shown in Fig. 16. Light is now injected into a clear fiber in a cone/collar assembly on the left of the photo. This assemply was borrowed from MINOS and is very similar to what will be in the full design. The fiber (not seen) loops around the apparatus and is aimed at the PMT (right). A diffuser is shown.

[3] D. Cherdack and W.A. Mann, *Magnetic Shielding Capabilities of the MINERvA PMT Box*, MINERνA note MINERvA-doc-164-v1.

[4] P. Adamson, et al., Nucl. Inst. Meth. A**492**, 325 (2002).

[5] P. Shanahan, priv. comm. (Nov., 2005).

[6] A. Cabrera, et al., NuMI-934 internal report.

[7] P. Harris (Sussex Univ.) provided excellent guidance and some pieces necessary for prototyping.